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Review of Screening Criteria and Technology for High Flow Fish Passage Systems in the Lower Columbia River

1.0 INTRODUCTION

The U.S. Army Corps of Engineers, Portland District is investigating methods of fish bypass through dams on the Columbia River. One of these bypass studies involves construction of a facility at Bonneville Dam First Powerhouse (B1) to collect and safely pass juvenile salmonids that are migrating downstream near the river surface. Due to the unprecedented large volumes of water expected to be required to effectively pass fish from the forebay into the bypass, the Corps is investigating methods to separate downstream migrants from the flow and pass the fish safely downstream in a lower volume flowline.

Existing criteria for dewatering facilities requires that screens be designed to ensure that water velocities approaching the screen face not exceed 0.40 feet per second (fps). Criteria for the maximum allowable approach velocity were developed to protect the smallest, and therefore, the weakest fish expected to pass a facility. Broad in coverage, existing screening criteria for the Columbia and Snake Rivers may be adjusted to environmental and biological conditions specific to a proposed project. In Section 2 of this report, we identified baseline environmental and biological conditions specific to B1. Our analysis identified conditions at B1, however the process and rationale are applicable to other Columbia and Snake River Projects.

To assist in the development of conventional design criteria for the B1 dewatering project, we reviewed existing dewatering criteria on the Columbia and Snake rivers and critically reviewed biological data on which criteria are based. As part of our review, we discussed aspects of screen design related to fish behavior and examined the classic definitions of approach and sweeping velocities (Section 3). In Section 4, we review background assumptions and analyses of conventional screening criteria and also describe the process used to adjust regional design criteria to environmental and biological conditions specific to B1.

Use of existing fish protection criteria for a conventional dewatering facility designed to handle high flow volumes (20,000 cfs) would require a screen area of 50,000 square feet. The sheer size of such a dewatering facility would present significant construction and operational difficulties. In Section 5 of this report, we review current advancements in high velocity dewatering technology that offer a potential alternative to conventional dewatering facilities. Eicher screen and modular inclined screen (MIS) technology is considered experimental, however prototype and full scale applications have achieved favorable results in Oregon, Washington, British Columbia, and New York.

2.0 BONNEVILLE DATA (ENVIRONMENTAL AND BIOLOGICAL) FOR DEWATERING SCREEN CRITERIA

Existing screen design criteria for the Columbia and Snake rivers were developed by the Washington Department of Fisheries to "protect fish in most situations expected" (Bates 1988). Screen criteria regulating the approach velocity (the component of water velocity that is perpendicular to the screen) were based on the water temperature and size of salmonid fry in an effort to provide 100% protection for the weakest fish present at any given time at a screening facility. The existing criteria for the Columbia and Snake rivers may be adjusted based on environmental and biological conditions specific to a proposed project. As part of our review of existing dewatering criteria, we identified baseline environmental and biological conditions that would be appropriate for the proposed dewatering facility on the Columbia River at B1.

The Bonneville Dam Project is located 40 miles east of Portland, Oregon at river mile (RM) 146.1. The project contains two hydroelectric generating facilities, spillways, fish ladders, and navigation locks. Each hydroelectric generating facility has a separate powerhouse. Bonneville Dam Powerhouse 1 went into operation in 1938, while Bonneville 2 came on-line in 1982 and essentially doubled the power generation capability at Bonneville Dam (USACOE on-line data 1997). Bonneville Dam creates a 20,600 acre reservoir with an average depth of 22.0 feet (WDF et al. 1990). Bonneville Pool is approximately 0.85 miles wide and 45.4 miles long. Full forebay depth for Bonneville Dam is 77.0 feet while normal depth varies from 71.5 to 76.5 feet (USACOE on-line data 1997). Bonneville 1 Powerhouse has a hydraulic capacity of 136,000 cubic feet per second (cfs).

A study is underway by the USACOE to investigate a surface collection facility at B1 (USACOE 1997a). During a brainstorming session held on 30 June, 1997, representatives from the USACOE and contractors concluded that the following surface collection alternatives be carried out to the 30 percent design level (ENSR 1997):

1) fry criteria conventional screens;
2) series or parallel high-velocity inclined screens;
3) high-velocity wall screens;
4) high-velocity inclined and wall screens;
5) louver primary dewatering system; and
6) channel floor (Coanda) dewatering screens

Flows entering the dewatering facility will range from 6,000 to 20,000 cfs. Due to the unprecedented volume of water expected to be required to pass fish from the forebay to the bypass via the surface collector, the USACOE is considering options to reduce this volume of

water (USACOE 1997a).
The following section identifies baseline environmental and biological factors pertinent to the design of a high volume dewatering facility at B1.

2.1 TIMING

Seasonal operation of the proposed dewatering facility will affect environmental and biological factors used to assess the swimming ability of juvenile salmonids and guide design criteria. Water temperature will be colder at an earlier start-up date, thus reducing the sustained swimming ability of juvenile fish. Turbidity levels can affect the reactive distance of juvenile salmonids and since turbidity in the Columbia River gradually increases to a peak in late May or early June (Martinson et al. 1995; 1996), the annual start of operation is important to establishing baseline conditions.

Target species and stock origin are both directly affected by the start-up date of the dewatering facility. The first appearance of a large number of subyearling chinook salmon at B1 coincides with the release of Spring Creek National Fish Hatchery (SCNFH) stock of chinook salmon (Table 2-1) (R. Martinson, NMFS, pers. comm.). Fish from the SCNFH are descendents of a Tule stock of fall chinook originating from the Wind and White Salmon rivers in 1901 (WDF et al. 1990). The SCNFH standard release schedule calls for 15-17 million juvenile chinook to be released on three dates; mid-March, mid-April, and mid-May (W.Tallow, USFWS, pers. comm.). Estimated fork lengths for those release dates are; 69 mm (2.7 inches) (mid-March), 86 mm (3.4 inches) (mid-April), and 105 mm 4.1 inches) (mid-May).

The passage of hatchery-origin subyearling Tule chinook salmon at B1 is followed by passage of yearling chinook, wild and hatchery steelhead, coho, and sockeye as expressed in their 10% passage dates (Table 2-2; Figure 2.1). The majority of subyearling bright chinook pass B1 later than the other species; peak passage of subyearling brights occurs in early June (Figure 2.1).

Table 2-1. Spring Creek National Fish Hatchery releases and peak passage dates at Bonneville Dam Powerhouse No. 1, 1994-1995 (Source: Martinson et. al 1995; 1996).

Release Date	Number Released	Peak Passage Past B1
18 March 1994	6,856,282	19 March 1994
15 April 1994	3,978,719	16 April 1994
20-21 May 1994	3,694,700	21 May 1994
16 March 1995	7,941,332	18 March 1995
15 April, 1995	4,257,254	15 April, 1995
20-21 May, 1995	3,800,000	20 May, 1995

Table 2-2. Estimated dates when a cumulative 10 percent of juvenile salmonid outmigrants pass Bonneville Dam Powerhouse 1 during 1994 and 1995 (Source: Martinson et. al 1995; 1996).

Species (stock)	1994	1995
Yearling chinook	19 April	18 April
Steelhead (wild)	28 April	27 April

Steelhead (hatchery)	3 May	4 May
Coho	9 May	26 April
Sockeye	13 May	9 May
Subyearling chinook (brights)	9 June	5 June

Annual start-up of the proposed dewatering facility at B1 is expected to begin on 1 March to protect mid-March releases from the Spring Creek Hatchery. Alternate start-up dates of 15 March and 1 April have been considered to coincide with later releases of hatchery-origin subyearling salmon. Passage of yearling salmonids at B1 typically does not occur until mid to late April (Table 2-2; Figure 2.1).

Data available from the National Marine Fisheries Service (NMFS) over the last three years does not allow a robust evaluation of the timing of downstream migrants passing B1. During 1994 and 1996, sampling of downstream migrants at B1 did not begin until 13 March. During 1995, sampling of downstream migrants began on 11 April (R. Martinson, NMFS, pers. comm.). During 1994, 99% of subyearling juvenile chinook passed B1 after 1 April; during 1996, 83% passed B1 after 1 April.

2.2 WATER TEMPERATURE

A positive correlation between swimming speed and water temperature has been demonstrated for juvenile salmonids for some modes of swimming (Griffiths and Alderdice 1972; Brett and Glass 1973; Glova and McInerney 1977; Smith and Carpenter 1987). Three primary swimming patterns have been characterized by Bell (1991) as cruising, sustained and burst or darting. Cruising refers to long term movement, such as ocean migration, that can be maintained for hours. At cruising speed, fish are capable of passing water over their gills at a rate necessary to satisfy oxygen requirements.

Sustained swimming refers to the maximum performance a fish can maintain for several minutes. Sustained swimming is characterized by continuous cyclic movements of the body and caudal fin and relies on red muscle and is driven by aerobic metabolism using fatty acids and glycogen for an energy source. In general, it is thought that sustained swimming performance increases with temperature up to a maximum or preferred temperature for a species, decreasing thereafter (Behlke et al. 1991).

Burst or darting refers to high velocity movement that can only be maintained for 5 to 15 seconds. During a burst movement a fish maintains cyclic tail-beat movements of small amplitude but of greater frequency than a sustained swimming pattern. Burst or darting swimming performance relies on white muscle and, unlike sustained swimming movements, is generally thought to be unaffected by temperature since this mode of locomotion uses anaerobic metabolism which relies mostly on glycogen as an energy source (Webb 1995).

Water temperatures for the Columbia River were obtained from the USACE for the period 1991 through 1996. These water temperatures were collected daily by the operator of B1 from well-mixed water within the scroll-case (M.T. Uhlir, USACOE, pers. comm.). Water temperatures on 1 March, 15 March, and 1 April are provided in Tables 2-3 through 2-5. Water temperatures averaged 4.9°C (40.8°F) on 1 March, 6.4°C (43.5°F) on 15 March, and 8.0°C (46.4°F) on 1 April for the period 1991-1996 in the Columbia River at B1 (Figures 2-2 through 2-7, see Appendix).

Water temperature increases gradually in the Columbia River throughout the summer and typically peaks in mid to late-August at an average of 22.5°C (72.5°F).

Table 2-3. Water temperature on 1 March in the Columbia River at Bonneville Dam Powerhouse 1 (Source: USACOE 1997b).

Year	Water Temperature (°C)	Water Temperature (°F)
1991	5	42
1992	7	45
1993	2	36
1994	4	40
1995	5	42
1996	4	40

Table 2-4. Water temperature on 15 March in the Columbia River at Bonneville Dam Powerhouse 1 (Source: USACOE 1997b).

Year	Water Temperature (°C)	Water Temperature (°F)
1991	6	43
1992	8	47
1993	4	40
1994	7	45
1995	7	45
1996	6	43

Table 2-5. Water temperature on 1 April in the Columbia River at Bonneville Dam Powerhouse 1 (Source: USACOE 1997b).

Year	Water Temperature (°C)	Water Temperature (°F)
1991	7	45
1992	10	50
1993	8	47
1994	9	48
1995	8	47
1996	8	47

2.3 DISSOLVED OXYGEN

The sustained swimming ability of juvenile salmonids is powered by aerobic respiration which, in part, is controlled by the available level of dissolved oxygen. Extreme low levels of oxygen can hinder fish movement while supersaturated levels of total dissolved gas can cause injury (i.e. gas-bubble trauma). Bell (1991) reported that swimming speed is reduced 60% when oxygen levels drop below 33% saturation. Low levels of dissolved oxygen should not affect maximum swimming speed of salmonids passing B1, since dissolved oxygen levels are expected to be at or near full saturation in the Columbia River at B1 during the peak outmigration season (Figure 2-8, see Appendix).

2.4 GAS BUBBLE TRAUMA

Gas bubble trauma, also referred to as gas bubble disease, came into prominence on the Columbia River system in the mid-1960's (Weitkamp and Katz 1980). The first widespread problem was identified during high flow events on the Columbia and Snake rivers, when dissolved gas levels reached 120%-130% in 1966 and 1967 (Weitkamp and Katz 1980).

Gas bubble trauma signs become apparent in fish through a physical process caused by the uncompensated "hyperbaric pressure of total gases" (Bouck 1980). When the pressure compensation is too great, gas bubble trauma forms blood embolisms, skin emphysema, and various physiological dysfunctions in aquatic organisms (Bouck 1980). Behavioral effects of gas bubble trauma include, but are not limited, to the loss of equilibrium, swimming speed, and predator avoidance Weitkamp and Katz 1980).

Shiewe (1974) studied the effects of dissolved gases upon swimming performance of juvenile chinook salmon. He found that swimming ability was significantly reduced from the exposure of chinook salmon to total gas pressures above 117%, the result being that these fish may be more susceptible to predation.

Martinson et al. (1996) examined 7,643 fish for signs of gas bubble trauma in 1995. Upon external examination, results indicated that very few (3 yearling chinook, 1 wild steelhead, and 1 coho) fish suffered from this infliction. Weitkamp and Katz (1980) found that gas bubble trauma symptoms are initially present in the form of internal lesions, thus not discernable through external evaluation. The examinations conducted by Martinson et al. (1996) may have underestimated the occurrence of gas bubble trauma on the Columbia River.

We recognize that gas bubble trauma is problematic on the lower Columbia River but adressing the effects total dissolved gas supersaturation is beyond the scope of this report.

2.5 TURBIDITY

The level of suspended solids in the water column, or turbidity, can reduce the reactive distance of juvenile salmonids (Bell 1991; Gregory 1993). If successful screening depends on active movement by juvenile salmonids in response to visual stimuli, a high level of turbidity (>20 NTU, nephelometric turbidity units) may affect screening performance. Avian predators may cause fish to occupy deeper parts of the water column when turbidity is low (<1 NTU), which could also affect screen performance (e.g. longer exposure time to inclined screens). Turbidity levels in the Columbia River during the smolt outmigration season are in the range of 2-3 NTUs (Figure 2-8, see Appendix), and are not expected to affect screening performance.

2.6 FISH SIZE

Swimming ability of juvenile fish increases with the size of the fish (Brett and Glass 1973; Webb 1995). Based on an extensive data set, Brett and Glass (1973) determined that the optimal cruising speed should increase by a factor of $5.9L^{0.53}$ at 5°C (41°F), where L is body length. Bell (1991) reported that the weight of the fish has been used to establish a 0.5 to 0.7 ratio of sustained swimming speed to darting swimming speed. Brett and Glass (1973) found that doubling the length of sockeye salmon had a greater effect on swimming speed than doubling the water temperature. As juvenile salmonids increase in size, they are better able to maintain locomotor control at higher water velocities.

Because the size of juvenile salmonids is considered critical in determining swimming ability, thus directly affecting screening criteria, the mean lengths of juvenile salmonids sampled at B1 from 1994 through 1996 were obtained from NMFS. Juvenile salmonids are sampled every hour from the entire bypass channel at B1 (R. Martinson, NMFS, pers. comm.). Samples are collected by lowering a wedgewire flume into the bypass channel at the end of an inclined screen, fish are then diverted into an aluminum tank at the end of the channel and are ready to be processed (Martinson et al. 1996). Two samples are obtained each hour, each sample of equal duration and lasting from 6 to 12 minutes, depending on the numbers of smolts passing through the bypass channel (Martinson et al. 1996). Outmigration at B1 has been monitored in the above fashion since 1984 .

Based on annual sampling at B1, sub-yearling chinook salmon are the smallest fish present at B1 during the outmigration period in the Columbia River (Martinson et al. 1995; 1996). Sub-yearling chinook at B1 averaged 60 mm fork length (2.4 inches) and 69 mm (2.7 inches) on 15 March, 1994 and 2 April, 1994, respectively (Figure 2-9). Sampling did not start until 11 April in 1995 (Figure 2-10), while sampling began on 23 March, 1996 when sub-yearling chinook averaged 74 mm fork length (2.9 inches) on 1 April (Figure 2-11).

A linear regression based on the mean length of sub-yearling chinook collected at B1 was calculated for the period 1994-1996 (Figure 2-12). Based on the regression equation:

mean sub-yearling chinook fork length in mm = 0.405(date) + 26.2 ($r=0.529$; $P=<0.0001$)

where "date" refers to the Julian calendar, the mean fork length for sub-yearling chinook salmon on 1 March is 51 mm (1.97 inches), on 15 March it is 57 mm (2.2 inches), and on 1 April they are 63 mm (2.5 inches) long. More than 98% of the sub-yearling chinook sampled at B1 during 1994-1996 averaged greater than 60 mm fork length (2.4 inches) (Figure 2-13). The mean fork length (weighted by number of fish) for sub-yearling chinook sampled during 1994-1996 was 96 mm (3.8 inches) (Figure 2-13). There will be salmonids smaller than 60 mm fork length (2.4 inches) passing B1, however, more than 98% of the subyearling chinook sampled from 1994 through 1996 were greater than 60 mm fork length (2.4 inches) (Figure 2-13). Yearling chinook, wild and hatchery steelhead, coho, and wild and hatchery sockeye smolts passing B1 are much larger than the subyearling chinook, and have an average fork length greater than 100 mm (3.9

inches) (Figures 2-14 through 2-16, see Appendix). By using average fork length, we recognize that smaller individuals may be present throughout the year in low densities at B1.

2.7 FISH SPECIES

Webb (1995) speculated that the piscivorous nature of chinook and coho while in the ocean may necessitate body and fin morphologies that are much different than pink, sockeye, and chum salmon who rely on less elusive zooplankton while in marine environments. These species-specific differences, that favor fast starts, acceleration, and maneuverability to intercept larger and faster food items, are likely to be greatest in juvenile fish (Webb 1995). While juvenile coho and chinook salmon display deeper bodies and larger fins than other species of salmon, significant differences in swimming ability have not been clearly identified (Webb 1995).

As previously noted, sub-yearling chinook are the smallest fish passing through B1 during the outmigration period (R. Martinson et al. 1995; 1996). Other species/life stages passing through the Columbia River at B1 during this time (March through October) include wild and hatchery sockeye salmon, coho salmon, hatchery and wild steelhead, along with yearling chinook (R. Martinson et al. 1995; 1996). Juvenile chinook and coho salmon may exhibit faster swimming speeds than sockeye salmon of the same body length, but available research is insufficient to delineate species-specific differences at B1.

2.8 STOCK ORIGIN

Differences in swimming speeds have been observed within different stocks of the same species (Taylor and McPhail 1985; Webb 1995), and between wild and hatchery-reared salmonid stocks. Juvenile coho from inland British Columbia streams were observed to have greater sustained swimming ability than juvenile coho from coastal streams, whereas juvenile coastal coho displayed enhanced burst swimming ability (Taylor and McPhail 1985). Salmonid juveniles raised in hatcheries are typically weaker than natural origin stocks (Bengeyfield 1994).

Most sub-yearling chinook passing B1 during the proposed early seasonal use of the dewatering facility are comprised of fish originating from SCNFH, located 30 miles upstream of B1 at Underwood, Washington (Delarm and Smith 1990). A few wild subyearling chinook salmon pass B1 early in the year, but accurate estimates of their numbers are unavailable (R. Martinson, NMFS, pers. comm.). If hatchery reared fish are weaker swimmers than their wild counterparts, juvenile chinook from the SCNFH may represent the weakest swimming salmonids passing B1.

There is also the possibility that hatchery origin smolts may exhibit higher guidance efficiencies than wild-origin smolts, since hatchery fish have prior experience with artificial structures. Cramer (1997) felt that salmon passing through one screening facility may be predisposed to pass through the following screen, thus improving fish guidance efficiency. We recognize the differences in swimming ability between wild and hatchery salmon stocks. Whether or not this difference occurs in the lower Columbia River salmon stocks is unknown at this time.

2.9 SUMMARY OF BIOTIC AND ABIOTIC FACTORS RELEVANT TO SCREEN DESIGN CRITERIA AT B1

Agency criteria for fish screens are typically based on the smallest and weakest fish present at a site. The factors affecting the smallest/weakest fish present during the outmigration period in the Columbia River at B1 beginning on 1 March, 15 March, or 1 April are as follows:

1 March
Water Temperature: 4.9° C (40.8°F)
Dissolved Oxygen: not expected to affect screening performance at B1
Gas Bubble Trauma: not expected to affect screening performance at B1
Turbidity: 2-3 NTU's
Fish Size: 50 mm (2.0 inches) [1]
Fish Species: juvenile chinook salmon
Stock Origin: Spring Creek National Fish Hatchery

15 March
Water Temperature: 6.4° C (43.5°F)
Dissolved Oxygen: not expected to affect screening performance at B1
Gas Bubble Trauma: not expected to affect screening performance at B1
Turbidity: 2-3 NTU's
Fish Size: 56 mm (2.2 inches)
Fish Species: juvenile chinook salmon
Stock Origin: Spring Creek National Fish Hatchery

1 April
Water Temperature: 8° C (46.4°F)
Dissolved Oxygen: not expected to affect screening performance at B1
Gas Bubble Trauma: not expected to affect screening performance at B1
Turbidity: 2-3 NTU's
Fish Size: 60 mm (2.4 inches)
Fish Species: juvenile chinook salmon
Stock Origin: Spring Creek National Fish Hatchery

[1] This value is extrapolated from data collected mid-March through June. No data are available on the size of juvenile salmonids passing B1 prior to mid-March.

3.0 FISH SCREEN HYDRAULICS AND FISH BEHAVIOR

3.1 ASPECTS OF SCREEN DESIGN RELATED TO FISH BEHAVIOR

Screen systems to keep fish out of intakes and diversions fall into two broad categories depending on the location and objective of the screen facility. Fish screens installed in lakes or other lentic systems are designed to exclude non-migratory fish from intakes using physical and behavioral (e.g. lights and sound) methods. These screen systems rely on fish sensing the intake or screen structure, and instinctively turning or swimming away from barriers and other perceived hazards. Other fish screens are installed along stream and river systems where most fish encountering the intake/screen system are actively migrating downstream. Design of screens installed to protect downstream migrating fish must consider the migratory behavior of fish to achieve successful performance.

Although designed for different objectives, some aspects of non-migratory fish behavior upstream of screens (or other barriers) in lakes is instructive to consider for design of fish screens in flowing water. Exclusion of fish from intakes in lake environments usually relies on the following:

- Intake and/or screen system design results in water velocities approaching the screen below the "cruising speed" of target species. "Cruising" or "sustained" speed is defined as a swimming speed that a fish can maintain for hours at a time (Bell 1991).
- Fish swimming in a lake may approach the screen head-on or at an angle. Fish typically detect the screen through visual or other sensory abilities and turn away before physically contacting the screen.
- Low water velocity in the vicinity of the screen allow fish to swim away from the screen, or swim in front of the screen ("hold") for a long period of time.

Fish residing in lakes may hold in front of intake screens for long periods of time, particularly if the flow pattern brings food to the intake location. They cannot maintain their cruising speed indefinitely, and periodically volitionally swim away to other areas of the lake. Resident fish screens with low water velocities in front of the screens usually work well because fish can easily turn away and the fish do not have an instinctive need to move past, or challenge the screen.

Application of the above screening pattern to stream and river intakes illustrates how migratory fish behavior demands a different design philosophy than used for resident fish. Prior to the 1980's, a large number of diversion systems on Pacific Northwest rivers included screens with low water velocity in front of the screens, and small-diameter pipe outlets or bypasses along the screen sides. Typically, these screens were installed perpendicular to the diversion alignment to minimize construction costs. It was anticipated that fish would hold in low-velocity water in front of the screens and at some point encounter the exits along the channel sides. Fish swimming into the exits would then travel downstream through the bypass, and back to the river. However, this proved ineffective for many downstream migrating fish.

Juvenile salmon typically migrate downstream tail-first. Downstream migrating fish encountering a screen oriented perpendicular to the diversion sense the obstruction, and activate their propulsion system (tail-beats) to stay away from the barrier. Since most pre-1980's screen systems were designed for slow water velocity approaching the screen, "cruising speed" was sufficient for most fish to hold in front of the screen for some period of time. During downstream migration, salmonid juveniles appear to be unwilling or unable to actively swim sideways or upstream searching for a route (bypass) around an obstruction (screen). Therefore, a large number of downstream migrating fish swam in front of pre-1980's screens to the point of exhaustion. At a minimum the screens delayed migration while some fish encountered the screen surface and incurred injury or mortality.

Delayed migration, injuries, and mortalities at screens oriented perpendicular to the flow resulted in development of screen systems angled to the flow, which is now the standard screen design criteria for migratory juvenile salmon in the Pacific Northwest (NMFS 1994). Numerous studies have shown that screens angled to the flow are much better at passing migratory fish than screens constructed perpendicular to the direction of water flow. This is because fish "holding" in front of the angled screens are continued to be carried downstream by the overall water flow, which passively directs downstream migrating fish to the bypass location(s). Numerous studies have also shown that screens with slow water velocity and an angled orientation effectively guide a large majority of fish to the bypass outlet. There appears to be a good match between hydraulic conditions specified in the fish screen criteria (NMFS 1994) and migratory fish behavior.

The above discussion shows that incorporating knowledge of fish behavior with proper hydraulic patterns are necessary for successful screen performance. Most advances in fish passage technology are based on repeated observations of successful installations. These observations are then incorporated into new installations. Few studies are directed at determining the physiological or behavioral basis for why a particular design successfully passes fish.

3.2 APPROACH VELOCITY AND SWEEPING VELOCITY TERMS FOR SCREEN DESIGN

The terms "approach velocity" and "sweeping velocity" are perhaps unique to fish passage design. Over the history of fish passage development, use of these terms has not been consistent, and they are often confused with other measures or expressions of water flow.

Definition of approach velocity and sweeping velocity in this report is consistent with the most widespread use in the Pacific Northwest; that is, consistent with region-wide fish passage criteria published by NMFS (1994) and WDFW (1995). From (NMFS 1994):

> "Approach velocity is the water velocity component perpendicular to and approximately three inches in front of the screen face."
>
> "Sweeping velocity is the water velocity component parallel (to) and adjacent to the screen face."

The water velocity components described by NMFS (1994) and WDFW (1995) are shown in Figure 3-1. It is important to keep in mind these "components" are algebraic vectors useful for quantitative descriptions of fish screens, but do not exist in physical form. The "approach velocity" term originated with early screen designs which, in most instances, were oriented perpendicular to the water flow direction. In this design case, "approach velocity" was equal to the average water velocity moving towards the screen surface, and the term had a physical counterpart. Fish swimming tests, generally done prior to the 1980's, evaluated the length of time that various fish species and life stages could swim directly into a current of known velocity. These tests correlated "approach velocity" with physical capabilities of salmon and other fish, and became the biological basis for fish screen criteria. Prior to the 1980's, screens were typically designed to have an "approach velocity" slower than the target fish species' cruising speed; angled screens and the "sweeping velocity" term were not yet in widespread use.

As fisheries biologists and screen designers observed the higher fish passage success with angled screens, there was substantial confusion regarding application of the term "approach velocity". "Approach velocity" was re-defined in the mid-1980's as a water velocity vector perpendicular to the screen orientation. This retained a commonly used term for fish screen criteria even though the physical reality was now substantially different. Re-definition of the "approach velocity" term was done by applying hydraulic engineering definitions typically used to isolate two-dimensional forces on structures. The overall water flow approaching screens was separated into two vector components as stated by NMFS (1994) above. The design criteria of most importance remained "approach velocity" (redefined from the late 1970's). The "sweeping velocity" term (origin unknown) is used to describe the velocity vector 90° from the approach velocity vector.

Biological studies of angled screen systems and re-definition of screen criteria terms occurred through the 1980's. Studies showed that screen systems designed in conformance with agency criteria (similar to NMFS 1994, WDFW 1995) effectively and safely passed almost all juvenile salmon. Empirical results supported the "approach velocity" and "sweeping velocity" criteria as a design basis. Use of these terms during the following discussion of conventional screening technology (Section 4) follows existing convention.

V = average water velocity in channel or conduit

V_a = vector perpendicular to screen ("approach velocity")

V_s = vector parallel with screen surface ('Sweeping velocity")

Figure 3-1. Water velocity vectors for screen design.

4.0 DEWATERING SCREEN CRITERIA FOR SUSTAINED SWIMMING

Existing design criteria for dewatering facilities in the Pacific Northwest rely on the sustained swimming performance of juvenile salmonids to avoid impingement. Design criteria are based on laboratory studies, field investigations, and the collective experience of resource agency representatives. The criteria are generally intended to be protective of a broad range of fish species, life stages, and environmental conditions. The application of these criteria to high flow dewatering facilities on the Columbia River at B1 would have a major influence on the size and cost of the facilities. This section will address the major factors affecting the design criteria for the facility with a focus on the criteria relating to the approach velocity.

State resource agencies including Washington, Oregon, California, Idaho, and Alaska have all either formally or informally adopted criteria consistent with that of the NMFS for approach velocity of screening facilities (NMFS 1994). The NMFS criteria were developed primarily for the protection of juvenile Pacific salmon, and are divided into two size classes, fry [<60 mm (2.4 inches)] and fingerlings [>60 mm (2.4 inches)]. The criteria specify a maximum allowable approach velocity of 0.4 feet per second (fps) for fry and 0.8 fps for fingerlings. They further specify that the sweeping velocity (parallel to the screen) should be equal to or greater than the approach velocity (normal to the screen). This second criteria requires that the screen angle not exceed 45° relative to the direction of flow. Furthermore, the agencies typically require that a fish be able to enter a bypass within one minute of encountering the screening facility, assuming fish are transported at the same speed as the “sweeping velocity”.

4.1 ALLOWABLE APPROACH VELOCITY

The approach velocity with respect to these design criteria is defined as the velocity component perpendicular to the screen and approximately 3 inches in front of the screen (NMFS 1994). Thus the velocity is calculated on the gross screen area instead of the screen open area (WDFW 1995). This velocity applies anywhere on the face of the screen, requiring either uniform flow distribution across the screen or increased screen area to compensate for nonuniformity.

4.2 BASIS FOR EXISTING GUIDELINES/CRITERIA - FRY

The approach velocity criteria have the greatest influence on the size and cost of a screening facility. For the high flow dewatering system under consideration for the Columbia River at B1, a system designed to control 15,000 cfs would require 37,500 ft^2 of screen using a design velocity of 0.4 fps.

Technical justification for the approach velocity criteria are summarized in a document prepared by the Washington Department of Fisheries (Bates 1988). These criteria are primarily based on the sustained swimming capability of juvenile salmonids. For salmonid fry, the technical justification relies heavily on laboratory studies conducted at the University of Washington (Smith and Carpenter 1987). These laboratory studies were investigations of the sustained swimming capability of young swim-up fry of five salmonid species (chinook, coho, chum, pink, and steelhead) under various water temperature conditions.

Salmonid eggs for the Smith and Carpenter (1987) investigations were obtained from both hatchery and wild stocks. The eggs were incubated at the University of Washington and tests were conducted when the juveniles were in the swim-up fry stage, representative of newly emerged fry in a stream, presumably the smallest and the weakest fish present. For all species tested, the size of the fry varied within a narrow range between 29 mm (1.1 inches) and 43 mm (1.7 inches). Tests were conducted at several water temperatures, 3° to 12° C (37.4 - 53.6°F). Smith and Carpenter (1987) tested swim-up fry of the following lengths:

Species	Size Range Tested
Chinook	36-43 mm (1.4 - 1.7 inches)
Coho	31-37 mm (1.2 - 1.5 inches)
Pink	28-37 mm (1.1 - 1.5 inches)
Chum	35-41 mm (1.4 - 1.6 inches)

For each temperature, 8 sets of stamina tests were completed with eight fry in each test. These tests were conducted to estimate the sustained swimming speed of individual fish based on a 15-minute stamina test. Mean critical velocities were then determined for each test group. Additional tests were conducted at velocities higher than the established sustained swimming speed to assess how long individual fish could sustain these higher velocities. All velocities were referenced to a single point in the test chamber, "point A" where the lowest velocities consistently occurred and where most fish eventually located prior to impingement.

The results of the laboratory tests indicated that the maximum sustained swimming speed is influenced by the water temperature, as well as the species and fork length of the fish. For all species, swimming performance increased with increasing water temperature and fork length. For the development of criteria, Bates (1988) selected

> *"…conservative sizes and temperatures, in favor of fish protection, are used in the recommendation in order to protect fish in most situations expected. It is expected that more or less stringent criteria might be applied where conditions are more or less severe.…"*

Based on a review of regional values, Bates (1988) selected a water temperature of 3°C (37.4°F) and a fork length of 40 mm (1.6 inches) was selected for criteria development. Applying data from the Smith and Carpenter (1987) study, a critical velocity was then selected based on the lower 95% data prediction interval. Bates (1988) stated:

> *" a summary definition of the initial critical velocity is as follows: The sample average critical velocity at 3 °C is 0.4 fps and we are 95% confident that the true average for a large number of groups is between 0.33 and 0.47. Since the true average could be as low as 0.33 fps, it is prudent to select this as the initial critical velocity."*

The statistical analysis of Smith and Carpenter (1987) suggested that there is a 95% confidence that the average critical velocity of many groups of eight fish is between 0.37 fps and 0.42 fps, and that there is a 95% confidence that the average for any single group of eight fish is between 0.33 and 0.47 fps. Thus, the "true average for a large number of groups" would be 0.37 fps instead of the 0.33 fps noted by Bates (1988).

Bates (1988) then adjusted the critical velocity estimates based on revised swim chamber calibration data. For chum salmon, the critical velocity was adjusted from 0.33 fps to 0.40 fps based on the revised calibration data. These adjusted critical velocities were estimated for each of the five species tested. It was noted that under the assumed conditions of water temperature and fork length, all species performed nearly equally with adjusted critical velocities of about 0.4 fps.

After selecting a critical velocity based on the above approach, a review was made of the weakest fish performance at the selected critical velocities. The "burst" test data of Smith and Carpenter (1987) were evaluated by Bates (1988) to determine the fatigue time for the weakest fish in a group. For each species he determined the expected time 97.5% of the poorest and second poorest performing fish could survive at the critical velocity. The shortest sustained time based on this analysis was 2.4 minutes for coho.

Based on the above analysis of the data, the recommended approach velocity criterion for screening where salmonid fry are present was set at 0.4 fps. Several conservative assumptions used in the application of Smith and Carpenter (1987) data to develop WDFW regional criteria are listed below:

- The Smith and Carpenter study referenced a calibration velocity selected at a point in the swim chamber with the lowest velocity, since fish typically eventually selected this location prior to fatiguing. The average velocity in the test chamber was about 50% higher than the velocity at "point A". Thus, during a considerable portion of a test, the fish were likely exposed to a range of velocities, the minimum of which may not be representative of the actual conditions experienced by the fish. Actual screening facilities have similar spatial variability in approach velocity even if care is taken in design to minimize any velocity "hot spots". Use of the minimum velocity measured in the Smith and Carpenter test chamber results in conservative approach velocity criteria.

- As intended, the criteria are protective of a wide range of fish sizes and water temperature conditions. They were developed for 40 mm fry (1.6 inches) at a water temperature of 3°C (37.4°F). For larger juveniles encountering a screening facility in warmer water, the criteria represent overly conservative design requirements.

- The statistical treatment of the Smith and Carpenter (1987) data discussed above also leads to a conservative estimate of the average sustained swimming ability of fry. The criteria was effectively set at the lower 95% confidence band for the mean of a group of eight fish rather than the confidence band for the mean of many groups of eight fish. However, raising the estimates of the critical velocity in the stamina tests would result in very short fatigue times for the weakest fish at the critical velocity, likely resulting in similar recommended velocity criteria.

- Sustained swimming tests are themselves a conservative approach to screening facilities that are designed with appropriate "sweeping velocities" and intended to pass juveniles within one to two minutes. Since the sweeping velocities should equal or exceed the screen approach velocities, weaker fish should naturally be transported through the screening facility as they fatigue. The laboratory tests that form the basis of the criteria do not replicate these flow conditions in screening facilities, nor do they incorporate the migratory behavior of the fish to accomplish safe passage.

4.3 BASIS FOR EXISTING GUIDELINES/CRITERIA - FINGERLINGS

The NMFS criteria guideline for screening approach velocity for fingerling size salmonids [>60mm(2.4 inches)] is 0.8 fps. A technical justification for this recommendation is described by Bates (1988), assuming target species were 60 mm in fork length (2.4 inches) and water temperature was 7°C (44.6°F). He reviewed the work of Griffiths and Alderdice (1972), Glova (1972), and Sazaki et al. (1972) to develop the approach velocity criteria. All of the investigators researched sustained swimming ability of juvenile salmonids. After reviewing the work of these researchers and adjusting critical velocity estimates for length and temperature, Bates (1988) estimated critical velocities ranging from 0.76 to 0.87 fps and noted that even the weakest juveniles could sustain velocities of 0.92 fps for 4 minutes.

Bates (1988) concluded there was insufficient data to develop approach velocities for juveniles in the same manner that he developed criteria recommendations for fry. We are unaware of any recent research that would change that conclusion.

4.4 APPLICATION TO THE LOWER COLUMBIA RIVER

During early March and April when juvenile fish migrate past Bonneville Dam, the fish are typically larger and the water temperatures are generally higher than those used in the development of regional guidelines for the approach velocity of screening facilities. The smallest fish passing B1 range from approximately 50 mm (2.0 inches) to 60mm (2.4 inches) in length and the water temperatures vary from 4.9°C (40.8°F) to 8°C (46.4°F) [in contrast to the guidelines basis of 40 mm (1.6 inches) and 3°C (37.4°F)].

The studies by Smith and Carpenter(1987) do not provide sufficient data to develop velocity criteria for the lower Columbia River that are consistent with the approach taken for the existing standards. The Smith and Carpenter (1987) study focused on swim-up fry generally less than 40 mm in length (1.6 inches). Few other similar studies exist. Glova and McInerney (1977) performed laboratory studies on the critical swimming speed for a range of sizes and temperature for juvenile coho salmon. Median critical swimming speed based on 1-hour stamina tests were determined for juveniles ranging from 40 mm to 110 mm in length (1.6 - 4.3 inches) in water temperatures of 3°C to 23°C (37.4 - 73.4°F). The results of the Glova and McInerney (1977) studies of coho along with those of Smith and Carpenter (1987) for 40 mm (1.6 inches) chinook salmon [as adjusted according to Bates (1988)] are presented in Figure 4-1. Both the mean and the lower 95% confidence prediction interval are shown for the Smith and Carpenter (1987) data. The mean data of Smith and Carpenter (1987) correspond very closely to the median data reported by Glova and McInerney (1977). The lower 95% confidence prediction interval is approximately 16% below the mean reported values.

The sustained swimming performance of fish generally increases with temperature up to a maximum or preferred temperature for a species, decreasing thereafter (Behlke et al. 1991). Bates (1988) used data from Smith and Carpenter (1987) and Glova and McInerney (1977) to develop correlations of water temperature to swimming speeds for various juvenile salmonids. The changes in swimming speed per 1°C change in water temperature reported by Bates (1988) for juvenile salmonids [<44 mm (1.7 inches)] are as follows:

Study	Species	Change in Swimming Speed
Glova and McInerney (1977)	Coho salmon	0.02 fps
Smith and Carpenter (1987)	Pink salmon	0.016 fps
Smith and Carpenter (1987)	Coho salmon	0.024 fps
Smith and Carpenter (1987)	Chinook salmon	0.036 fps

In consideration of the range of reported values, Bates (1988) developed a general assumption of an increase of 0.02 fps in swimming speed for every 1.0°C increase in water temperature between 4°C (39.2°F) and 15°C (59°F) for all juvenile salmon species.

Sub-yearling chinook salmon are the smallest fish present at B1 on 1 April (Martinson et al. 1995; 1996). Using the general assumption developed by Bates (1988), the swimming ability of sub-yearling chinook can be adjusted by 0.02 fps for every 1°C change in water temperature. Existing NMFS criteria for the Columbia and Snake Rivers assume a water temperature of 3°C (37.4°F) for fry based on Bates (1988) review of western Washington river systems. Measurements of water temperature collected at the B1 scroll case indicate water temperatures are 4.9°C (40.8°F) on 1 March, 6.4°C (43.5°F) on 15 March, and 8°C (46.4°F) on 1 April.

Based on an extrapolation of fish length data gathered by the NMFS at B1, the average fork length of subyearling chinook on 1 March is 51 mm (2.0 inches). Measurement of subyearling chinook outmigrants at B1 during mid-March indicate a fork length of 57 mm (2.2 inches) by 15 March and a fork length of 63 mm (2.4 inches) by 1 April. We recognize that in using the average fork length, there may be a few smaller salmon passing B1.

Three methods are presented below to identify critical velocity design criteria by examining the sustained swimming performance of the weakest fish of the size range and at water temperatures expected at B1.

Method 1

The first method adjusts regional criteria to the fish lengths and water temperatures measured at B1 as recommended by Bates (1988). Regional NMFS and WDFW approach velocity design criteria are 0.40 fps in the absence of site-specific data. Using the 0.016 fps increase in critical swimming speed per 1 mm increase in fork length adjustment cited in Bates (1988), the swimming speed for 51 mm (2.0 inches), 57 mm (2.2 inches), and 63 mm (2.4 inches) sub-yearling chinook salmon would increase by 0.18 fps to 0.32 fps compared to 40 mm (1.6 inches) chinook (Table 4-1). Adjusting regional approach velocity criteria for both fish length and water temperatures according to Bates (1988), results in design criteria for B1 of 0.61 fps on 1 March, 0.72 fps on 15 March, and 0.85 fps on 1 April (Method 1, Tables 4-1 through 4-3).

Method 2

The second method identifies the weakest swimming performance of 40 mm fish at the water temperatures expected at B1 and then increases the velocity to reflect the larger size of B1 fish. Referring to Smith and Carpenter (1987), the source document used by regulatory agencies, we used the value at the lower 95% confidence band to estimate the weakest swimming performance of 40 mm fish at B1 water temperatures (Figure 4-1). This critical velocity was then increased to reflect the increased size, and therefore faster sustained swimming speeds, of B1 fish using an adjustment derived from the data of Glova and McInerney (1977). Based on data collected by Glova and McInerney, the swimming speed of juvenile coho increases about 0.012 fps per mm of fork length. Adjusting the weakest expected swimming performance of 40 mm fish by increased size of B1 fish yields estimated critical swimming speeds of subyearling chinook at B1 of 0.61 fps for 51 mm (2.0 inches) juveniles on 1 March, 0.74 fps for 57 mm (2.2 inches) juveniles on 15 March, and 0.88 fps for 63 mm (2.4 inches) juveniles on 1 April (Method 2, Tables 4-1 through 4-3).

Method 3

The third method relies on the work of Glova and McInerney (1977) to establish the median swimming performance of fish of a size and at water temperatures expected at B1. This swimming performance is then reduced to reflect the weaker fish of that size range. The median swimming performances based on the Glova and McInerney (1977) data are: 0.70 fps for a 51 mm (2.0 inches) fish at 4.9°C (40.8°F); 0.85 fps for a 57 mm (2.2 inches) fish at 6.4°C (43.5°F);

and 0.97 fps for a 63 mm (2.4 inches) fish at 8°C (46.4°F) (Figure 4-2). If we assume that the weakest fish can sustain velocities 16% less than the median for several minutes (based on Smith

and Carpenter 1987, lower 95% confidence band), the equivalent critical velocities are: 0.59 fps on 1 March, 0.71 fps on 15 March, and 0.82 fps on 1 April (Method 3, Tables 4-1 through 4-3).

Alternate approach velocity criteria for the proposed dewatering facility at B1 were identified by averaging the results of the three methods for seasonal operation starting on 1 March, 15 March and 1 April and rounding to the nearest tenth of foot per second.

Table 4-1. Summary of calibrated critical velocities for conventional screening for 1 March.

Source	Species	Fork Length	Water Temperature	Calibrated Critical Velocity
NMFS Regional Criteria		40 mm (1.7 inches)	3°C (37.4°F)	0.40 fps
Method 1	Chinook	51 mm (2.0 inches)	4.9°C (40.8°F)	0.61 fps
Method 2	Chinook	51 mm (2.0 inches)	4.9°C (40.8°F)	0.61 fps
Method 3	Chinook	51 mm (2.0 inches)	4.9°C (40.8°F)	0.58 fps
Alternate approach velocity criteria assuming a 1 March start-up				0.60 fps[2]

Table 4-2. Summary of calibrated critical velocities for conventional screening for 15 March.

Source	Species	Fork Length	Water Temperature	Calibrated Critical Velocity
NMFS Regional Criteria		40 mm (1.7 inches)	3°C (37.4°F)	0.40 fps
Method 1	Chinook	57 mm (2.2 inches)	6.4°C (43.5°F)	0.72 fps
Method 2	Chinook	57 mm (2.2 inches)	6.4°C (43.5°F)	0.73 fps
Method 3	Chinook	57 mm (2.2 inches)	6.4°C (43.5°F)	0.70 fps
Alternate approach velocity criteria assuming a 15 March start-up				0.70 fps

Table 4-3. Summary of calibrated critical velocities for conventional screening for 1 April.

Source	Species	Fork Length	Water Temperature	Calibrated Critical Velocity
NMFS Regional Criteria		40 mm (1.7 inches)	3°C (37.4°F)	0.40 fps
Method 1	Chinook	63 mm (2.4 inches)	8°C (46.4°F)	0.82 fps
Method 2	Chinook	63 mm (2.4 inches)	8°C (46.4°F)	0.84 fps
Method 3	Chinook	63 mm (2.4 inches)	8°C (46.4°F)	0.79 fps
Alternate approach velocity criteria assuming a 1 April start-up				0.80 fps

[2] These values are based on fish lengths extrapolated from data collected mid-March through June. No data are available on the size of juvenile salmonids passing B1 prior to mid-March.

4.5 SUMMARY

Existing screening criteria rely heavily on the analysis conducted by Bates (1988) of the laboratory tests conducted by Smith and Carpenter (1987) at the University of Washington. The analysis consisted of determining the mean velocity that swim-up fry can sustain for a minimum of 15 minutes (critical velocity) with the confirmation that the weakest fish can sustain this velocity for at least 2 minutes. In all cases, Bates (1988) found that the weakest fish could sustain the critical velocity for 2 minutes, but not significantly longer. As discussed in section 4.2, Bates' analysis of the mean performance of fry in developing the critical velocity was conservative (low). However, the stated objective to protect the weakest fish limits any significant adjustments to the critical velocities. Even if the estimate of the mean swimming performance of the fry were increased, the weakest fish fatigue quickly at those higher velocities and would fail the 2 minute sustained swimming criteria.

The current NMFS fry criteria of 0.4 fps (40mm; 3°C) and fingerling criteria of 0.8 fps (60mm; 7°C) were developed based on regional environmental and biological conditions. Where site-specific data are available, the regional criteria can be modified to ensure target species are protected. Several years of site-specific data were available from monitoring of salmonid outmigrants at B1. Application of these data using three alternate methods yielded a fairly consistent pattern. Methods 1, 2, and 3 resulted in approach velocity design criteria of 0.6 fps for a 1 March start-up date for the proposed dewatering facility to 0.8 fps for a 1 April annual start-up date.

Existing design criteria for dewatering facilities in the Pacific Northwest rely on the sustained swimming performance of juvenile salmonids to avoid impingement. Because sustained swimming patterns are powered by red muscle fiber, an extended recovery period is required before maximum red muscle exertion can be repeated. As salmonid fry become fatigued, they may switch swimming patterns and use a burst and coast gait to conserve rapidly depleting reserves (Smith and Carpenter 1987). This burst and coast swimming pattern may be powered by white and red muscle fibers and may completely exhaust the energy reserves of the fish. When completely fatigued, salmonid fry are particularly susceptible to injury, disease or predation. Dewatering facilities that are designed to accommodate sustained swimming performance may exhaust the energy reserves of a fish and not provide the expected level of resource protection.

5.0 DEVELOPMENT OF DEWATERING CRITERIA FOR SALMON DARTING BEHAVIOR

Screens inclined from horizontal have been used for years to separate salmon from diverted flow. Examples of screens of this type include: fish screen bypass dewatering for fish sampling in

Yakima River basin (smolt monitoring facilities), Baker Project surface collector system dewatering screens, and several locations in British Columbia. In recent years, two patented designs for inclined screens have shown promise for safely separating young salmon from diverted flow at relatively high water velocities. The two screen types are the Eicher Screen (Eicher 1981) and modular inclined screen (MIS) (Taft et. al. 1992). This report section reviews design criteria that would be appropriate for installation of these screen types at Bonneville Dam, with possible application to dewatering the large flow rate expected from proposed surface bypass facilities.

Eicher Screens and modular inclined screens are very similar in design elements and they are considered equivalent fish passage systems in this report. They both evolved from open-channel inclined plane screens that have been used for separation of water and fish. Eicher Screens and MIS have essentially the same hydraulic patterns. Both screen systems rely on the following sequence for successful fish passage:

- Fish move down the diversion conduit in relatively high water velocity (4 to 10 feet per second) and are able to maintain normal swimming posture (pointed upstream, body upright).

- Fish detect and/or touch screen or fluid boundary layer and fish dart away to avoid obstruction.

- Rapid water velocity in conduit carries fish towards bypass location as they dart away from screen.

The fish darting behavior observed during Eicher Screen and MIS testing is a rapid forward thrust combined with upward turning. This fish movement occurs over a time period measured in seconds (or fraction of a second) rather than the sustained swimming behavior used to develop existing agency screen criteria (NMFS 1994; WDFW 1995). It is unknown whether the upward turning motion is instinctively upward or a motion away from the screen.

Eicher Screen and MIS testing to date includes six locations where juvenile salmon have successfully passed these screen types at water velocities that substantially exceed agency screen design criteria. These locations are the T.W. Sullivan Hydroelectric Plant (Eicher 1981), University of Washington laboratory (Eicher Associates 1987), Elwha Hydroelectric Project (Stone & Webster 1992), Alden Research Laboratory (Stone & Webster 1994), Puntledge Diversion Dam (Bengeyfield 1995), and Green Island Hydroelectric Project (Stone & Webster and Alden Research Laboratory 1996).

Most advances in fish passage technology are based on installation of new facilities followed by studies to verify screening performance. A brief description of successful fish passage tests for Eicher Screens and MIS are summarized in a following report. Tests at the six high-velocity screen installations cited above have demonstrated that juvenile salmon are capable of safely bypassing high-velocity screens under certain hydraulic conditions and within certain physical limits. However, the reasons why have not yet been identified. There is little understanding of the specific fish behavior or instincts that allow small fish to avoid screens under high velocity conditions. Human understanding of fish behavior and capabilities is rudimentary. However, we have repeatedly learned that apparent fish behavior and design criteria applicable to one set of circumstances does not necessarily lead to the proper approach at other sites or under other circumstances.

5.1 FISH SCREEN TERMINOLOGY RE-VISITED

"Approach velocity" and "sweeping velocity" are human concepts useful for fish screen design under low water velocity conditions. However, this terminology has muddled a number of elements of fish passage design, and it would be beneficial to change the terminology. The reasons why are outlined in this section, along with recommendations for alternative and more meaningful terms.

The "approach velocity" term as currently defined is a misnomer. First, the term is a leftover from pre-1980's screen designs when "approach velocity" matched average water velocity in the diversion system. This is no longer the case. "Approach velocity" no longer has a physical counterpart. Second, the term is not consistently used in the fish passage field, with "approach velocity" meaning different things in different parts of the country. At least some of these differences are caused by retaining and re-defining a commonly used term, even though the physical reality has changed. Third and most important, fish do not sense separate velocity components in the overall flow.

The following criteria for fish screen design would conform to current agency criteria such as NMFS (1994) and WDFW (1995), with respect to water velocity and direction moving towards a screen surface:

- Angle of screen $\leq 45°$ with respect to water flow direction.
- Average water velocity in channel moving towards screen $\leq$ (0.4 fps)/(sine of screen angle)

These two criteria would replace the "approach velocity" and "sweeping velocity" criteria and would have several advantages.

- The angle of screen and average water velocity in the channel are physical features of screen installations, probably sensed by fish. These variables are real, not mathematical vectors.
- Dropping the "approach velocity" term would eliminate confusion related to differing uses of the term.
- Use of the sine function in the criteria would correctly indicate this criterion is a mathematical calculation, rather than a physical feature ("approach velocity" implies a physical counterpart).

Similar screen criteria could be defined to replace other terms in agency criteria, to more accurately describe screen characteristics. For instance, a maximum screen length upstream of a bypass could be specified as: (60*cosine screen angle*average water velocity in diversion channel). This would be better than the equivalent agency criteria of "(intermediate bypasses) shall be employed if the sweeping velocity will not move fish to the bypass within 60 seconds, assuming fish are transported at this velocity" (NMFS 1994).

For instance, existing agency criteria states "(intermediate bypasses) shall be employed if the sweeping velocity will not move the fish to the bypass within 60 seconds, assuming fish are transported at this velocity." This criteria effectively limits the maximum length of the screen. Mathematically, this criteria could be stated; maximum screen length = 60*cosine screen angle*average water velocity in the channel. For example, if the screen angle is 18° and the average water velocity in the channel is 7 fps, then the screen length would be limited to no more than 399 feet.

The following screen design features (Figure 5-1) should be the primary basis for criteria development and terminology (screen materials, etc. are considered secondary in this report):

- Average water velocity in the channel or conduit approaching the screen.
- Screen angle with respect to flow, including designation of vertical or horizontal angle. Screen angle would be inter-related with average water velocity, and this relationship would be determined through biological studies.
- Maximum screen length before a bypass is required. This would be a function of average water velocity and screen angle, with appropriate constants determined empirically.
- Average water velocity entering the bypass. This may be expressed as a multiple of average water velocity flowing down the channel approaching the screens.
- Bypass flow rate expressed as a fraction of total diversion flow rate.

The variables listed above, with appropriate inter-relationships, mathematical functions, and constants from empirical studies would be sufficient to replace the artificial terms "approach velocity" and "sweeping velocity" in state-of-the-art screen design criteria. These variables would all be clearly understood since they would all have only one meaning corresponding to their physical reality. This group of variables would define the most important screen design criteria with respect to successful fish passage and would also be paramount factors in determination of screen size and cost.

The "approach velocity" and "sweeping velocity" terms are not used further in this report. Instead, the variables recommended above are used to evaluate fish passage data for Eicher screens and MIS.

Figure 5-1. Recommended variables for fish screen design.

5.2 REVIEW OF FISH PASSAGE TESTING FOR EICHER SCREENS AND MIS

This section includes a detailed review for six locations where fish passage by Eicher Screens and MIS have been evaluated under controlled conditions. Fish passage tests considered representative of high-velocity Eicher Screen and MIS technology include tests at the University of Washington laboratory (Eicher Screen, 1984-1985), Elwha Dam (Eicher Screen, 1990-1991), Alden Research Laboratory (MIS, 1992-1993), Puntledge Hydroelectric Project (Eicher Screen, 1993-1994), and Green Island Hydroelectric Project (MIS, 1995). Data summaries and references for these biological studies are included in this review.

The prototype Eicher Screen installed at the T.W. Sullivan Plant was installed and tested in the mid-1980's. Early tests at the T.W. Sullivan Plant were hampered by the complicated site layout, non-uniform hydraulic patterns upstream and downstream of the screen, and lack of good capture and holding facilities for bypassed fish (Eicher Associates 1987). Since 1992, improved testing procedures have been instituted at the plant and more useful data have been collected (Cramer 1997). Much of the data collected at the T.W. Sullivan plant since 1992 have been collected under unsteady flow conditions. While the data provided valuable documentation of a successful high velocity screen, the inability keep flow conditions constant during the testing process limited broader use of the data in our review.

Fish passage tests with Eicher Screens and MIS have been done under a variety of water temperature conditions and with salmonid total length (TL) ranging from about 40 mm to 200 mm (Figure 5-2). Data sets for salmon and trout less than 100 mm total length and under cold water temperatures (< 12° C) were considered most useful for determination of high-velocity screen criteria for the Bonneville Powerhouse location (see Section 2). The following section of this report uses data sets plotted within the ellipse on Figure 5-2 to determine reasonable design criteria for high-velocity dewatering screens at Bonneville. In addition, the data from the T.W. Sullivan plant are included although the range of temperature and fish sizes varied during the tests.

Eicher Screen and MIS testing with juvenile salmon and trout has evaluated "successful" fish passage using a variety of methods for injury assessment and calculation of fish passage rates. Fish injury and mortality data from these tests have been reviewed and "standardized" for this report (Table 5-1). Overall, it was assumed that salmon and trout passing these screens with less than 10% scale loss, no apparent injuries (bruises, etc.) and alive would be considered "without injury". This categorization was used in this report to evaluate how screen characteristics affected fish passage.

The classification of fish injury in this report (visible injury or > 10% scale loss) was more stringent than used in most of the studies cited in Table 5-1. The 10% scale loss "threshold" was used in this report because it provided a consistent level for comparison between studies. A review of the results of individual tests indicates that the selection of a higher threshold affects estimates of injury but does not alter trends in the data.

Table 5-1. Fish injury assessment for determination of Eicher Screen and MIS design criteria.

Eicher Screen or MIS Test Location	Reference	Fish Condition Required for Classification as "Without Injury"
University of Washington Lab	Eicher Associates 1987	Alive without external injury Scale loss < 10%
Elwha Dam	Stone & Webster 1992	Alive without external injury Scale loss < 10%
Alden Research Lab	Stone & Webster 1994	Alive without external injury Scale loss < 10%
Puntledge Hydroelectric Project	Bengeyfield 1994 and Bengeyfield 1995	Alive without external injury Scale loss < 16% (<10% not reported)
Green Island Hydroelectric Project	Stone & Webster and Alden Research Laboratory 1996	Alive without external injury Scale loss < 10%
T. W. Sullivan Plant	Cramer 1997	Alive without external injury Scale loss < 20%(<10% not reported)

Several tests of Eicher Screens and MIS included "delayed mortality" or "latent mortality" studies where bypassed fish were held for varying lengths of time (24 to 144 hours) to determine the possible effects of injury on survival. A review of test data concluded that the number of fish dying during the "delayed mortality" tests was almost always less than the number of fish considered injured (> 10% scale loss or other injury). It was assumed that the fish dying during these tests were fish categorized as "injured" after passing through the screen and bypass facilities; however, there was no way to check this assumption. The test data used in this report does not include "delayed mortality" data since it was presumed inclusion of these data would be "double-counting" injury rates for bypassed fish.

5.3 CRITERIA DEVELOPMENT FOR EICHER SCREENS AND MIS

This section reviews data for Eicher Screen and MIS testing with consideration for applicability to high-velocity dewatering screens at Bonneville Dam.

5.3.1 Screen Angle, Material, and Porosity

The first observation with respect to Eicher Screen and MIS tests is that all tests used essentially the same screen angle, screen material, and screen porosity (Table 5-2). Therefore, without additional test data and lacking complete understanding of fish behavior relative to screen inclination, existing information would limit the screening facility at Bonneville Dam to the following requirements:

- Screen angle 15 to 19° from alignment of approach channel, assuming approach channel is horizontal or moderately inclined. The screen plane is inclined from horizontal, not vertical.

- Screen surface material constructed with stainless steel wedgewire bars with 2 mm bar width and openings between bars of 2 mm. This results in screen porosity of 50%.

Table 5-2. Eicher Screen and MIS angle, screen material, and screen porosity used in biological tests.

Reference	Screen Angle from Approach Channel or Conduit	Screen Material	Screen Porosity
Eicher Associates 1987	16°	Stainless steel wedgewire with 2 mm bar width & 2 mm openings	50%
Stone & Webster 1992	16°	Stainless steel wedgewire with 1.9 mm bar width & 0.2 mm to 3.2 mm openings	8% to 63% (mostly 63%)
Stone & Webster 1994	15°	Stainless steel wedgewire with 2 mm bar width & 2 mm openings	50%
Bengeyfield 1994 and 1995	16.5°	Stainless steel wedgewire with 1.8 mm bar width & 2.5 mm openings	58%
Stone & Webster and Alden Research Laboratory 1996	15°	Stainless steel wedgewire with 2 mm bar width & 2 mm openings	50%
Cramer 1997	19°	Stainless steel wedgewire with 2 mm bar width & 2 mm openings	50%

5.3.2 Mean Conduit/Channel Velocity

One screen design variable of paramount importance is the average water velocity in the channel or conduit approaching Eicher Screen or MIS facilities. This variable affects the ability of fish to maintain a normal swimming posture in the approach channel, determines the energy and/or darting speed needed to avoid the screen, may affect other (unknown) aspects of fish behavior and response, and is the most important variable in determining overall screen size and cost.

Salmon and trout fry injury rates increased when water velocities in the approach channel exceeded 6 feet per second (fps) during Eicher Screen and MIS tests (Figure 5-3). This graph shows the level of fish injury for several salmonid species with total length ranging from 40 to 100 mm. Water temperatures ranged from 7 to 12° C, and the screens were clear of debris during these tests. Different salmonid species are not identified on Figure 5-3 because species differences were considered secondary to other variables (water velocity, fish length, etc.).

The level of fish injury was plotted versus the square of water velocity in Figure 5-3 on the basis that the energy and/or force required to avoid contact with the screen might be correlated with injury level. For all tests, the level of fish injury was less than 5% for Eicher Screen and MIS facilities where the approach channel velocity was 6 fps or less. Where velocities were 6 fps or less, fish injury rates varied for each test with no clear relationship between water velocity (squared) and fish injury. Fish injury rates were substantially higher for water velocities exceeding 6 fps. For tests with water velocity above 6 fps, fish injury rates were highly variable and ranged from 0% to 22% (Figure 5-3). It should be noted that the available data are dominated by the tests conducted at Elwha Dam. With the exception of the tests conducted at 10 fps (Alden Research Laboratory tests), all high injury tests were conducted at Elwha. There is no clear reason for the variability in the test data. The lowest data point (78% passage without injury) was a test performed at Elwha on 99 mm chinook at 10°C with a penstock velocity of 7.8 fps and an equivalent bypass velocity. A near identical test was performed using a slightly higher increased bypass velocity which resulted in a passage without injury rate of 84%. Thus, a relatively minor change in the physical configuration had a significant impact on the injury level.

Thus, Figure 5-3 suggests that for velocities greater than 6 fps, significant increases in injury may occur for a Eicher/MIS type screening facility. The scatter in the data suggests that factors other than velocity play a role in the level of injury that occurs. Fish passage data sets for 6 fps were reviewed to see if there were any relationships between fish injury and other variables. These reviews provided some insights into how screen design or fish species or size variables may affect fish injury rates.

5.3.3 Fish Length

For Eicher screens and MIS tested at 6 fps, the rate of fish injury appeared higher for fish of approximately 100 mm total length, compared to smaller salmon and trout fry (Figure 5-4). The apparent inverse relationship between fish length and “passage without injury” for screens with 6 fps water velocity conflicts with the common assumption that larger fish should be able to avoid screens better than small fish. Eicher Associates (1987) observed that small fish rapidly swept through the Eicher Screen test facility at the University of Washington laboratory contacted the screen less often than larger fish who could maintain position by swimming vigorously upstream of the screen. These observations may partly explain the relationship shown in Figure 5-4, or other variables may be the cause. Regardless, test data do not support the assumption that 100 mm salmonid fry should have less injury and/or mortality than smaller salmonid fry under equal water velocity conditions.

5.3.4 Screen Length

There appeared to be an inverse relationship between screen length and the percentage of fish that were not injured during high-velocity (6 fps) screen tests (Figure 5-5). Possible reasons for this relationship may be that the longer screens resulted in more frequent fish contacts (resulting in injury), longer screens were also wider resulting in a larger solid plate convergence zone into the bypass conduit, and/or relative scale effects between fish and screen facilities. There are not enough data to explain the relationship shown in Figure 5-5; however, the practical result is that screen length appears to influence injury potential. No testing has been completed for screens over about 40 feet in length and increased injury appears to occur for screen length greater than about 20 feet (at 6 fps water velocity).

5.3.5 Bypass Velocity

Most Eicher Screen and MIS tests have been done with bypass entrance water velocities equal to or greater than the average water velocity approaching the screen facility. The empirical basis for high bypass water velocity is best outlined by Eicher Associates (1987) who also suggested that bypass velocities exceeding channel approach velocities may assist fish passage. This possibility is not supported by Eicher Screen and MIS test data for fish species, sizes, and water temperature conditions relevant to Bonneville Dam (Figure 5-6). There does not appear to be any relationship between fish injury and bypass velocities ranging from 1.0 to 1.3 times the approach channel water velocity.

5.3.6 Bypass Flow Rate

The flow rate into the bypass is an important design criterion for Eicher Screens and MIS. Higher flow rates into the bypass would intuitively predict higher fish passage success, and experimental data supports this for bypass flow rates between 5% and 11% (0.88 – 25 cfs) of total flow (Figure 5-7). Screen facilities tested with bypass flow rates of about 11% of total flow (0.88 cfs) resulted in less fish injury than screen systems with bypass flow equal to 5% (2.3-25 cfs) of total flow. It is unknown if bypass flow rates above 11% (0.88 cfs) of total flow would further decrease fish injury, since injury at this bypass level appears very low (Figure 5-7, Tables 5-4 and 5-5).

5.3.7 Water Temperature

Water temperature did not appear to affect the rate of fish injury for high-velocity screens examined in this section (6 fps water velocity, < 100 mm fry TL, 6-12° C temperature range). A common assumption in fish screen design is that colder water temperatures adversely affect fish passage success, due to decreased fish swimming speed or stamina in cold water. A relationship between water temperature and fish injury rate was not observed for Eicher Screens and MIS data reviewed in this report (Figure 5-8). The lack of correlation between water temperature and fish injury rate is consistent with the assumption that high velocity screens rely on fast-start swimming movement which is generally thought to be unaffected by temperature.

5.3.8 Effects of Debris on Fish Injury at High-Velocity Screens

This section evaluates how debris collecting on Eicher Screens or MIS may affect fish passage. Fish passage tests with introduced debris were done at the Elwha Dam location (Stone & Webster 1992) using chinook salmon less than 100 mm total length and water temperatures less than 12° C (similar to limiting conditions for Bonneville). In these tests, the amount of debris accumulated on the Eicher Screen was measured as an incremental increase in head loss through the screen. Head loss is a measure of energy expended, in this case directly related to the amount of screen blockage and turbulence created by the debris.

There was a strong relationship between head loss caused by debris and fish injury rates in the Elwha Dam tests (Figure 5-9); these tests were for chinook salmon in two size categories tested at the 6 fps water velocity condition. Debris accumulations causing head loss as low as 0.05 feet resulted in significant increases in injury rates for small chinook salmon. Injury rates increased as head loss due to debris increased (Figure 5-9).

Natural rates of debris accumulation, and the resulting head losses at Eicher Screen and MIS facilities have not been rigorously studied. The best information related to debris effects during long-term operation of high-velocity screens is reported by Bengeyfield (1994 and 1995) for the Eicher Screens installed in the Puntledge Hydroelectric Project penstocks (6 fps water velocity). From Bengeyfield (1994), “By the end of the study however (approximately 9 weeks duration), a gradual build-up of debris was evident that the backwashing process was unable to dislodge from the screens. These accumulations often formed around supple, thin branches which initially penetrated the screen slots and became wrapped around the screen support bars. The protruding twigs then appeared to entangle leaves and other debris.”

Head losses due to the debris accumulated on the Puntledge screens were not reported by Bengeyfield (1994) so it is difficult to directly compare these observations with experimental data (e.g. Figure 5-9). However, an incremental head loss of 0.05 feet with a nominal loss across the screens of about 1.0 feet (5% increase in head loss) constitutes a velocity increase of about 2% through the screens. Thus, debris accumulations covering about 2% of the screen area would result in an incremental head loss of 0.05 feet, if the nominal water velocity in the approach channel was 6 fps. According to the relationship between fish injury and head loss shown in Figure 5-9, this could be sufficient to cause a noticeable increase in fish injury.

Review of available data on debris loading suggests that small increases in the velocity through the screens has a significant impact on the injury to fish. Thus, something much more important than through-screen velocity must play a role in the injury relationship. This may be associated with direct interaction of the fish with the debris, or possible effects of the debris on the flow field through the facility. Regardless of the cause, the type of debris may be an important factor affecting this relationship. Insufficient data are available to evaluate these hypotheses.

The rate of chinook salmon injury was much less sensitive to head losses from debris when water velocity in the approach channel was 4 fps instead of 6 fps (Figure 5-10). These tests were identical to those described above for 6 fps water velocity, except for the reduced water velocity in the approach channel. For chinook salmon fry tested at Elwha Dam (Stone & Webster 1992), fish injury rates at the 4 fps water velocity condition did not appear to increase until head loss caused by debris was in the range of 0.2 feet.

Available data from the Elwha tests suggest that if debris loading is a concern at the project, significant injury could be expected for channel or penstock velocities of 6 fps or greater. This is likely dependent on the amount and type of debris, but available data are insufficient to assess this aspect.

5.4 SUMMARY

Design criteria for high volume dewatering facilities being considered at Bonneville Dam will reflect the collective experience of state, federal and private fish passage engineers gained through tests and experimentation at other projects, but also may reflect constraints specific to the project. Some of the constraints at Bonneville Dam involve biological and environmental site conditions, but design considerations may also involve social and economic justifications. To assist in the development of design criteria for the Bonneville Dam dewatering project, we reviewed present dewatering criteria on the Columbia and Snake Rivers and critically reviewed biological data on which criteria are based. Appropriate design criteria for the high volume dewatering facility under consideration at Bonneville may involve factors beyond our purview, therefore we have restricted our discussion to technical considerations.

We identified six dewatering projects where fish passage using Eicher and MIS technology had been evaluated using releases of marked juvenile salmonids (Table 5-3). We did not assess the veracity of conclusions reached by previous researchers at these projects. Instead, we pooled available data that approximated environmental conditions and target size range of fish at Bonneville Dam. The six identified studies provided a data set of 45 separate controlled tests of high velocity technology. Our analysis of these data indicated that at average conduit velocities of 6 fps or less, and under clean screen conditions, more than 95 percent of juvenile salmonids were consistently diverted from the flowline with less than 10 percent injury. At conduit velocities of 7 fps and greater, the observed rate of injury and mortality was equivocal.

Sixteen of the 45 tests in our data set involved conduit velocities of more than 6 fps. In six of those tests, more than 5 percent of the fish were injured or killed. We defined injury as fish that incurred more than 10 percent descaling. Of the six tests where more than 5 percent injury was observed, five of the tests were conducted at the Elwha Project. The reason for variability of high velocity test results at the Elwha Project could not be conclusively determined. Elwha project researchers believe that the variable screen porosity was the primary reason for injuries, but could not explain the reason for variability of test results (A. Solonsky, pers. comm.). The Elwha testing protocol was the product of extensive review and over $1 million was expended on the tests. Sample sizes ranged from 150 to 800 fish per test release and recovery procedures were rigorously implemented. The variable screen porosity is a feature unique to the Elwha, but without additional information, the variability of Elwha test results leads to concern over future application of high velocity technology at conduit velocities greater than 6 fps.

Dewatering facilities using high velocity technology are presently considered to be experimental and are developed on a case-by-base basis. The proposed use of Eicher screen and MIS technology at the Wynoochee and Howard Hanson Dam projects in Washington State include up to 40 different design criteria to guide protection of outmigrating salmonid smolts. These design criteria were developed based on the knowledge of state and federal fish passage engineers and biologists and experience gained through performance testing of facilities at primarily Pacific Northwest locations. For the high velocity screens proposed at the Wynoochee and Howard

Hanson Dam projects, the maximum conduit design velocity is 6 fps. Potential application of high velocity technology using conduit velocities over 6 fps should incorporate a rigorous testing of prototype facilities using fish collected at proposed passage sites.

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7.0 APPENDIX